Open Ocean Swell Dispersion from Moving Wind Fetches

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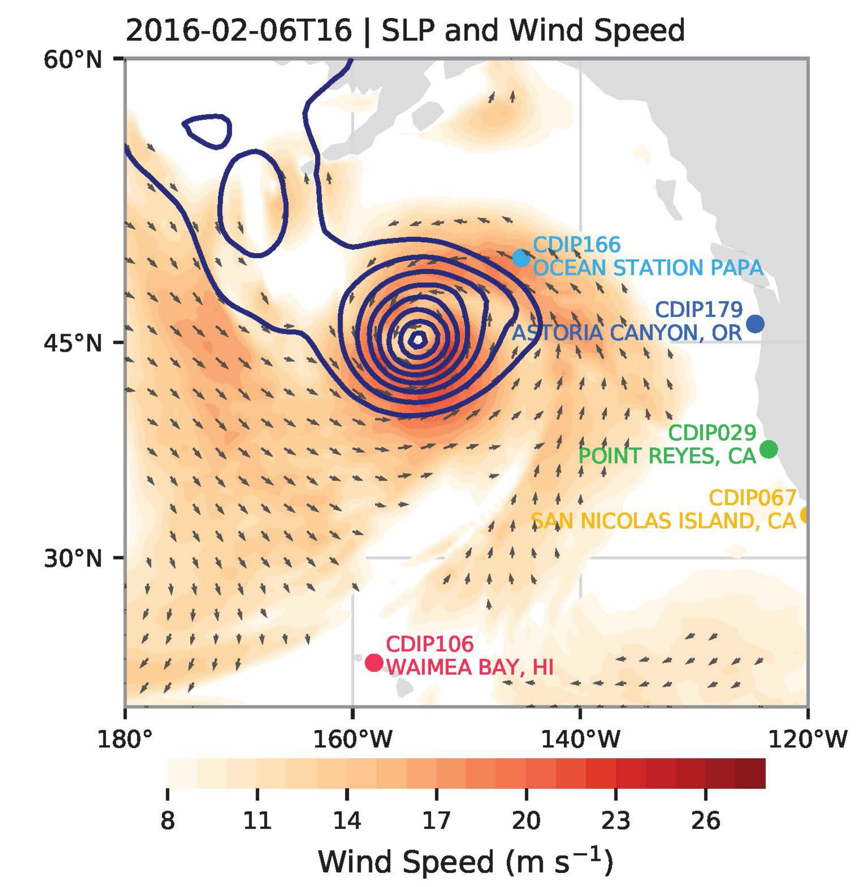
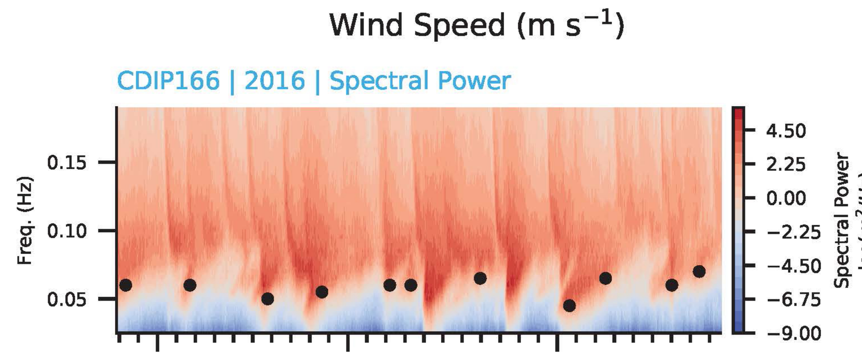
The paradigm of moving storms and point sources of swell

Extra-tropical storms generate areas of high wind speed called fetch. The fetch size, duration, and peak wind speed are strongly linked to the storm's intensity, such that changes in the storm intensity will also affect the generation of swell waves.

The storm's fetch forms swell that is observed at a fair distance from the source region. Wave buoys along the US West Coast and Hawaii detect multiple wave events per month (see figures on the right), each of which has a characteristic slope that can be used to infer the origin of the swell event. This can be done by inverting the dispersion relation for linear deep-water waves to a distance and initial time of the swell source (Munk, 1947, Barber and Ursell, 1948, Collard et. al, 2009, Hell et. al, 2019). However, it remains unclear how moving large fetches can create swell that seems to appear from a point source in the open ocean.





The evolution of the wave peak circle frequency ω_p for a steep sea can be described by

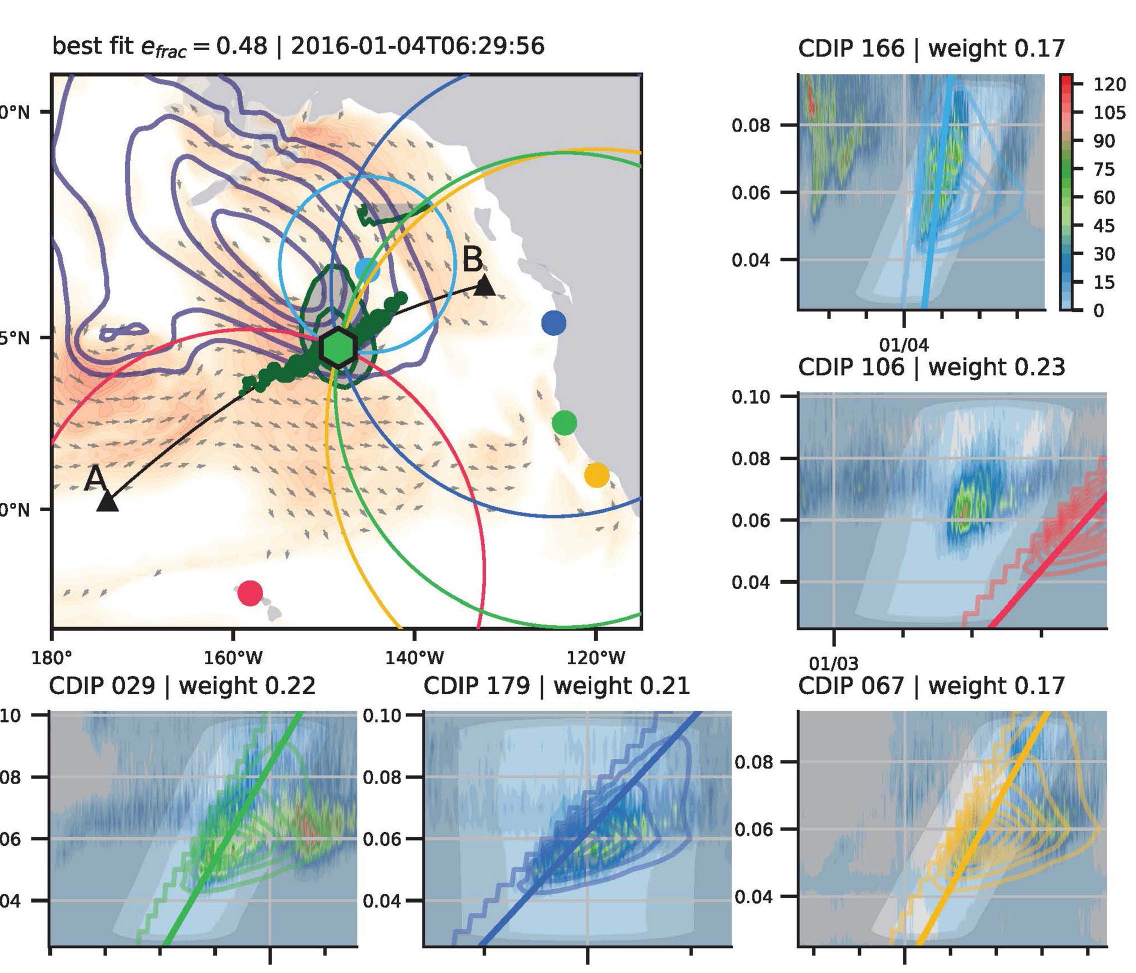
$$\partial_t \omega_p + (c_g - V)\, \partial_X \omega_p = \kappa(q)\, u^{(-2-\frac{1}{q})}\, \omega_p^{-\frac{1}{q}}, \quad (1)$$

where $c_g(\omega_p)$ the group velocity of waves, V the translational velocity of the storm, u the 10-meter wind speed and κ a constant that depends on the sea state (Kudryavtsev et. al 2015, Hasselmann et. al, 1976).

Localizing swell sources

Adapting Hell et. al 2019 for a multistation optimization method

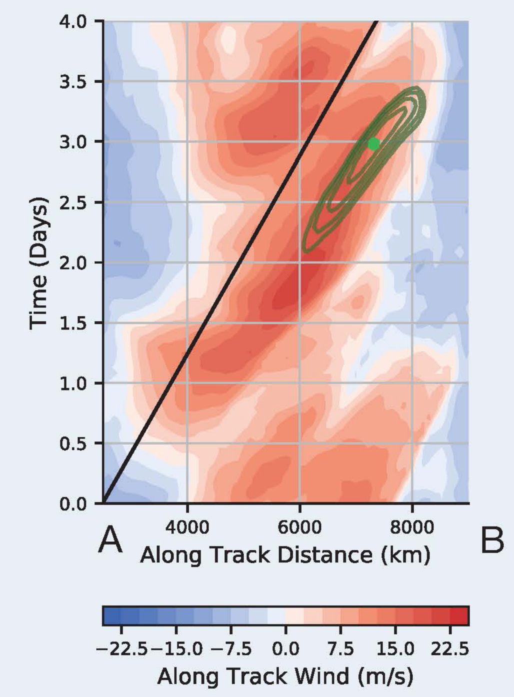
First, the individual events are used to optimize a model of swell arrivals in each station separately. A supervised machine learning algorithm fits a parametric model that is based on the JONSWAP spectrum in frequency and a Gamma-distribution in time (JONSWAP, Hasselmann et. al, 1973). The fitted model estimates the slope of the dispersed swell arrival and provides the initial time and radial distance of the wave event (Munk, 1947, Barder and Ursell, 1948).



Wave events of a similar initial time are then identified using data from the five selected wave buoys to optimize a second parametric model that describes the initial spectrum at the source point based on the parametric wave model from Hell et. al 2019. This accounts for amplitude attenuation with travel distance (Ardhuin et. al, 2009) and decay of the spectral peak enhancement.

A case study of a North Pacific storm

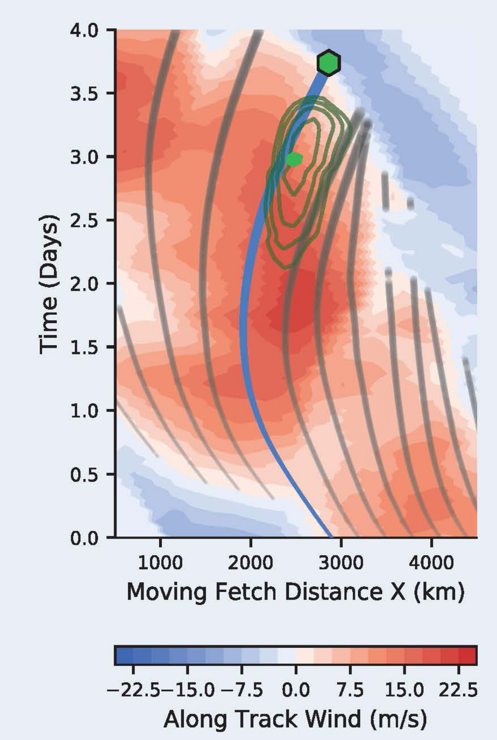
with a translational velocity of 14 m/s



ERA5 winds along the trace of best model fit

The time-dependent winds of the moving fetch are taken from the trace best-fitted models (from A to B). The fetch's estimated velocity is about 14 m/s (black line).

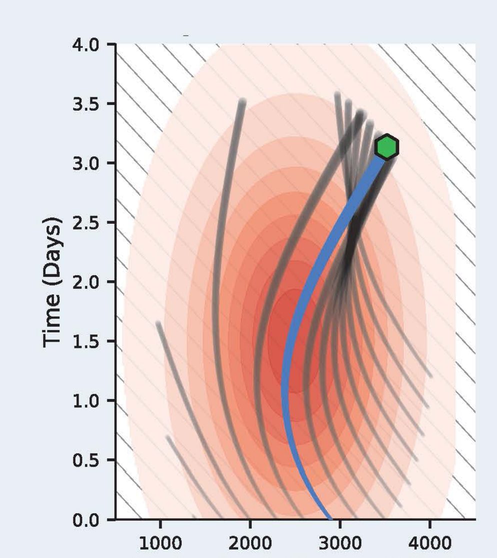
- the green contours show the region of most likely wave origin (model fit > 60%).
- the green dot indicates the best-fitted position for the source point of highest wave energy derived from wave buoy observations (see left column).



ERA5 winds under the moving fetch & contour integrals

- Wind speeds are remapped in the frame of the moving fetch
- Eq. (1) is solved by using the method of characteristics given the winds in the moving frame. Black contour shows the path of wave energy packets as they propagate and grow in the moving fetch.
- The blue contour is the path of the highest wave energy and lowest peak frequency resulting in a source-point at the green hexagon.

In the case of perfect winds and wave observations, the optimized and propagated wave energy would occur at the same location.



2D Gaussian representation of the wind in the moving frame

The observed wind pattern is simplified to a Gaussian forcing under the moving storm with a peak wind speed of 22 m/s, a width of 700 km, and a height of 1 day.

The peak wind speed is important for generating the location of the highest wave energy convergence.

References

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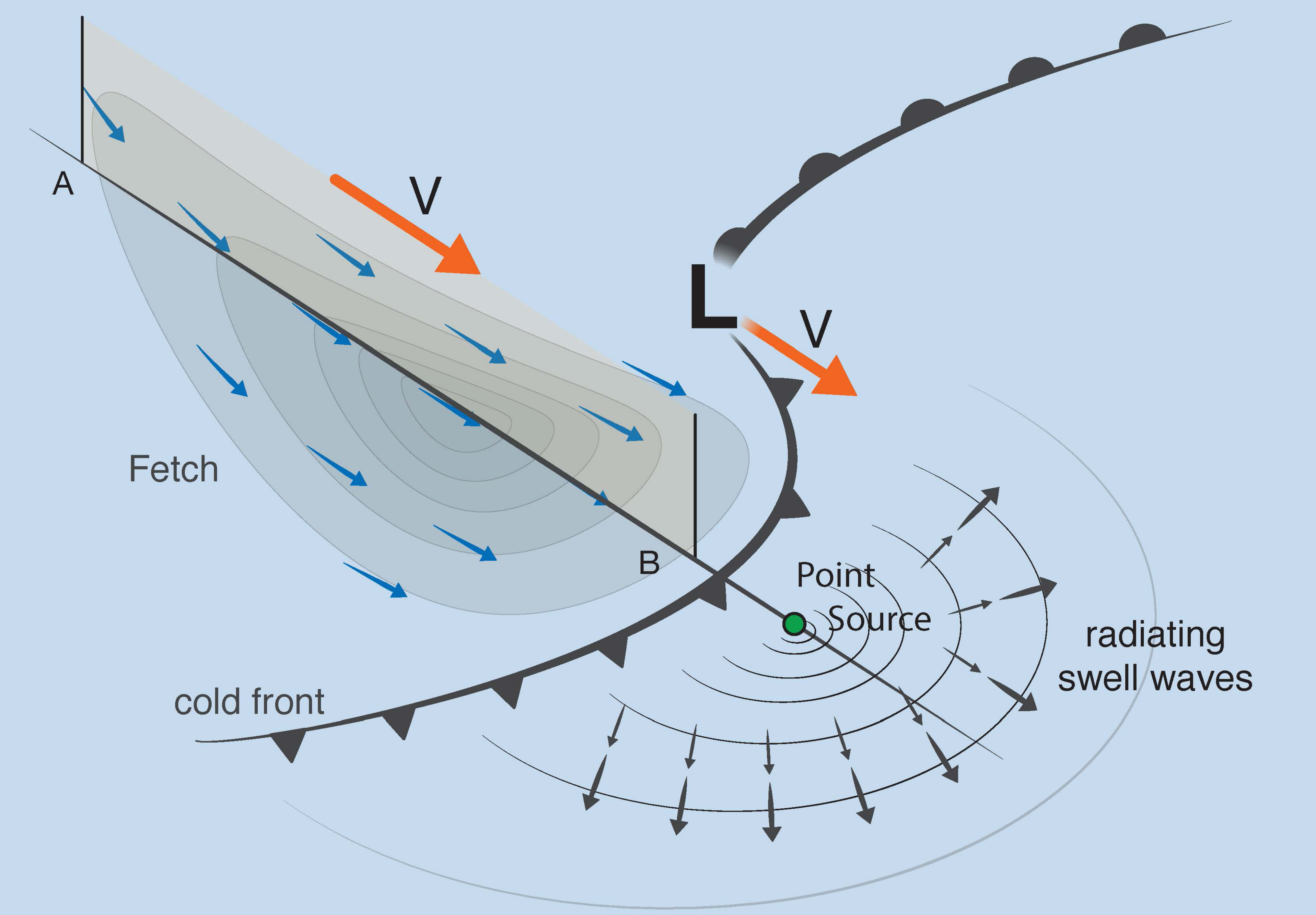
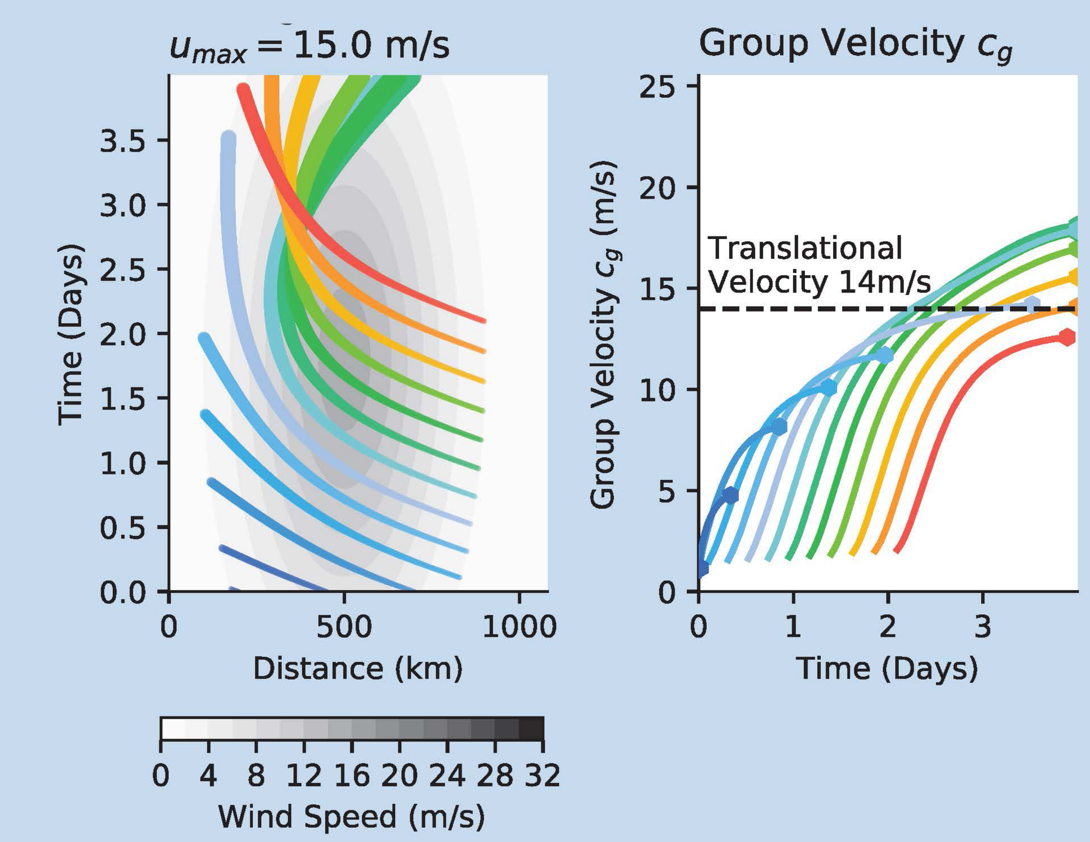


Simple models for storms generating poin souces of swell

Two ways to focus wave energy with varying winds under a moving fetch

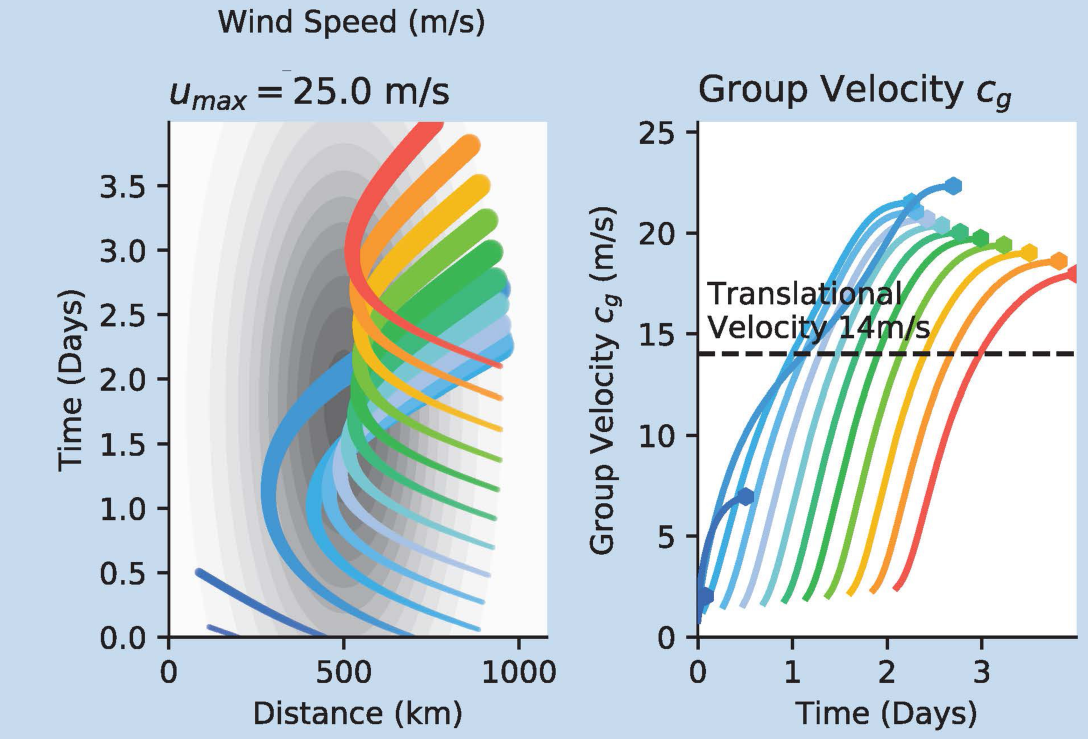
Time-limited case

A weak moving fetch of typical size, that is 95% of the wind forcing is within 800 km and 6 days with a maximum wind speed of 15 m/s, generates wave energy that is focused when the fetch decays (~day 4) at about the center of the moving fetch with a peak period of 23 sec (0.043 Hz).

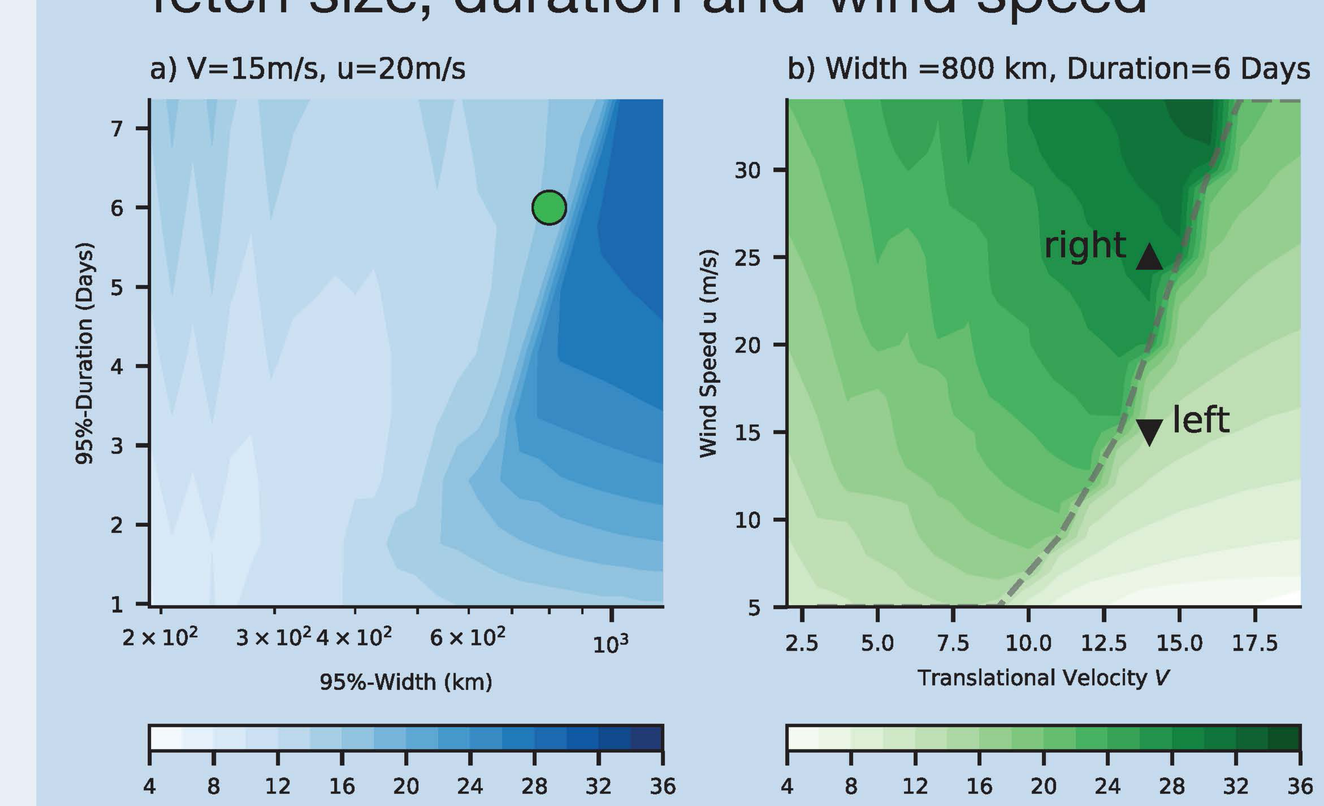


Fetch limited case

A strong moving fetch of the same size by a peak wind speed of 25 m/s results in wave energy convergence at the fetch edge. Assuming no interaction between the ray paths, the lowest peak period is about 28 sec (0.035 Hz).



Swell peak period dependence on fetch size, duration and wind speed



(left) *dependence of the largest peak period on width and duration of the Gaussian wind field. The green dot shows the parameters of the plot on on the right.*

(right) *dependence of the largest peak period on translational velocity V and wind speed u. The black dashed line marks the transition between a time-limited and fetch-limited storm. The triangles show the postion of the parameters from cases above.*